LIGHTWEIGHT STRUCTURES FOR SYDNEY 2000 OLYMPICS: UPDATE

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Introduction
One of the privileges of working in the Australian construction market, compared say to the US or European markets, is that its relatively small size discourages the adoption of "standard" solutions for large-span, large-volume enclosures like multi-purpose arenas and stadia. So the Olympic facilities recently completed at Homebush Bay, Sydney, are a riot of spectacular roof shapes: all different and all very creative as individual responses to unique briefs. They are a credit to the imagination, design skills, and supply, fabrication and erection capabilities of the local lightweight structures industry.

Sydney Olympic structures of note completed in the last two years include:

- Showring Stadium
- Stadium Australia 2000
- Superdome Multi-Use Arena
- RAS Halls
- Sydney Olympic Tennis Centre
- Velodrome, Bankstown
- Sydney Indoor Sports Centre
- Olympic Park Railway Station
- Hockey Centre
- Equestrian Centre, Horsley Park

Homebush Bay facilities to be used during the Olympics, and completed prior to '97 include:

- International Aquatic Centre
- National Athletics Stadium
- State Sports Centre

Many of these structures have been reported and published previously. In particular, papers on 1,2,3,8,9,11, feature in the Proceedings of LSA98, the International IASS / LSAA / IEAust Conference on Lightweight Structures, held in Sydney, September '98.

The present paper describes the structure of projects 4,5,6 above, for which Ove Arup and Partners were consulting engineers.

Tennis Centre

Introduction
The Sydney Olympic Tennis Centre, Homebush Bay, will be the venue for the 2000 Olympic and Paralympic tennis events in Sydney, and the future headquarters of Tennis NSW, hosting in particular the NSW Open - the official warm up event to the Australian Open.

The complex comprises a 10,000 seat Centre Court, two show courts and seven other match courts, six practice courts and a players' facilities / administration building, all on a large reclaimed site at Homebush Bay.

Lawrence Nield and Partners, Architects in collaboration with Ove Arup and Partners, Consulting Engineers (Civil, Structural, Mechanical, Electrical, Hydraulics, Fire Services, Traffic and Acoustics) won the Master plan and Design competition, organised by the Olympic Coordination Authority, in December 1997. The Tennis Centre was completed in November 1999.

Structure
The plan of the centre court is segmental, with twenty-four repeating radial modules, approximating a circular layout. This configuration maximised structural simplicity, while also exploiting maximum structural efficiency and economy of materials through repetition of the segment module.

Each radial segment is formed by corresponding radial tier beams, raked at approximately 30 degrees to provide good spectator sight lines to the court. Given the likelihood of variable crowd live loading segment to segment, hence torsional loading on the raking tier beam supporting the edges of the segments, a fabricated square hollow section raking tier beam was chosen, for its torsional stiffness and strength. Primary vertical support to each tier beam frame is provided by "V" columns, which divides the tier beam into three approximately equal spans. Rather than directly propping the perimeter tip of each beam, a more efficient system of support is achieved by a combination of hanging from the mast tip, and lateral restraint from the two tensile tie rings, one at top of mast level, the other at the beam tip. This arrangement has the further advantage of leaving the space beneath the tier beams completely free, enhancing the dramatic appearance of the cantilever portion of the seating bowl.

Precast prestressed L shaped beams forms the seating plats. The raking of the tier beam governs the available depth of each seat plat, which in turn implies an optimum span for structural efficiency thereby dictating the number of radial segments. By making an in-situ joint between seat plats as they are stacked one on top of each other, the raking beams are linked in Vierendeel fashion. This, coupled with the bracing between the perimeter rings, controls relative movement between adjacent tier beams under pattern live loading. Finally, the faceted circular layout of the precast seating units is susceptible to high thermal hoop stresses. To minimise this effect, every second precast unit is axially released via an oversize hole sliding joint.

The barrel vaulted roof shade to the grandstand seating is achieved by simple radial arched beams, supported using a combined system of hanging from the central mast and complimentary thrusting respectively onto the inner and outer perimeter rings, with a further support provided through a pinned connection to the mast. Purlins, carrying metal decking, then span between the curved beams to complete the roof structure.

Velodrome

Introduction
The Sydney Olympic Velodrome is an indoor venue approximately 130m long by 100m wide with an elliptical plan shape. The architectural concept is for a sleek, low-slung shape, roofed with a shallow rise metal shell. Approximately 3000 permanent seats are provided, with provision for 3000 temporary seats for the Olympic mode and for other large events. The building is sited at "The Crest", an existing recreational field in the shire of Bankstown, Sydney

Additional facilities included in the venue include a licensed club, offices for the Australian Cycling Federation, and parking for over 100 cars. The Architect was Ryder-SJPH, with Ove Arup and Partners as consulting engineers.

Structure
After a detailed options study, a single layer grid shell was chosen to support the roof for reasons of economy, aesthetics and buildability. The obvious alternative solution using curved trusses was more expensive and less desirable architecturally. A single-layer grid-shell is a very effective solution for spanning medium to large distances. The surface of the shell must be fully triangulated to maximise shear stiffness and so to minimise displacements, moments, effective lengths, and consequent second order effects.

A range of different patterns was considered initially for the doubly curved shell surface, including orthogonal and geodesic patterns. The chosen solution was based on a torus, with a generatrix arc radius of 110m and a directrix radius of 142m. To achieve the desired elliptical plan shape, some undulation in elevation of the perimeter of the shell occurs, producing a transverse rise measured from the edge elevation of 13m and a longitudinal rise of 16m.

Fabricated box-section arches on the circular generatrix lines span across the hall, at approximately 11m centres. The box sections are 900mm deep and taper from a 450mm by 16pl flange at the top down to 380mm by 20pl flange at the base. The taper reflects in section the segments defined by the torus. The high bending stiffness of the box-section arches is advantageous as it provides useful out-of-plane stiffness to help prevent buckling of the whole shell.

The construction benefit of the box-section arches is that large lengths can be lifted in one piece, spanning long distances under self-weight, and enabling the geometry of the roof to be quickly and easily fixed. Laced between each box arch are large diameter tube sections that shed the load diagonally across the roof into the more tightly curved corners of the ring beam.

The outward thrust of the shell is resisted by a 600mm diameter steel tube ring beam, with a wall plate thickness of 20mm.The ring beam also supports the gutter sections, and provides a top restraint for the perimeter façade structure.

Vertical roof loads are transferred from the shell roof elements via the ring beam into inclined V-columns that stand free of the perimeter façade. The V-columns are inclined outwards and pick up pairs of box arches. Global stability of the roof is provided by wall cross bracing 60mm in diameter, in the same plane as the columns, at six locations around the perimeter. Pairs of back-to-back cold-formed 250mm deep "C" purlins at 1.8m centres span the 11m between box section arches The roof cladding is BHP "Brownbuild 305" profiled metal deck.

Potential instability was considered at local member level for flexural / axial / torsional modes, and globally by both eigenvalue methods and non-linear methods, with simulation of adverse initial imperfections. Account was also taken of the necessary stiffness to prevent local snap through buckling. Such behaviour also required a non-linear model. The Arup structural analysis package "Fablon" was used to verify that sufficient geometric and shear stiffness existed so that onset of a ductile failure of the ring beam would occur before snap through instability.

Ras Exhibition Halls

Introduction

The new Royal Agricultural Society (RAS) Exhibition Halls at Homebush Bay will serve as a key venue for Olympic indoor sports, including volleyball, handball, badminton, and rhythmic gymnastics, and for paralympic events including basketball, handball and volleyball. The halls provide 22,000m^2 of continuous exhibition area, also divisible into four separate spaces by operable acoustic doors. One hall, larger than the others, is roofed by a 100m diameter dome that has become a landmark for Olympic Park. The three adjacent and contiguous rectangular halls, each 67m x 72m, are roofed with cylindrical vaults.

In early 1996, Ancher Mortlock Woolley were appointed by the OCA as architects for the halls, with Ove Arup and Partners providing engineering design services across the structural, civil, mechanical, electrical, hydraulic, passive energy, and acoustics disciplines.

Environmentally, the Halls embody the Government's goal of "the Green Olympics". The roof structures are of plantation pine with its low embodied energy, low CO_2 generation, and high carbon fixing potential. The efficiency of the shell-like framing ensures low material consumption. The halls are naturally ventilated, and are partly naturally lit. The dome also has a very energy-efficient air-conditioning system, which requires substantially less cooling energy than traditional systems.

Structure

Both dome and rectangular roof vaults are single-layer reticulated shell structures. The choice of single-layer minimised the intrusion of structure into the halls, thereby maximising useable volume. The fully triangulated framing patterns maximise shear stiffness and so minimise displacements and buckling tendencies. Joints were conceived as moment-capable, to further increase stiffness and simplify fabrication.

Comparative designs were carried out, and "all-steel" and "maximum-timber" solutions were costed. Although timber was expected to be marginally more expensive than steel, it was chosen for its environmental benefits and for its links to traditional RAS facilities.

Buckling modes and effective lengths for the dome were analysed, and checks carried out on combined stresses in both timber and steel members. Continuously curved CHS steel purlins stabilise the timber sections by cleats which grip their top edges. Individual glulam timber members were tested in non-linear models to check the effectiveness of the purlins in stabilising the deep timber cross-sections in torsion. The results were interpreted in terms of effective lengths for axial compression and for negative bending (bottom edge compression), for design by code-based methods.

At tender, the main joints were shown with steel shoes attached to the ends of each glulam member, and split radially and circumferentially to permit any sequence of member sub-assembly and erection. Of all the methods available, that finally chosen by the contractor was unusual, but very effective. Starting with the central monitor structure propped off the slab, successive rings of timber members were installed, closed with their CHS tie rings, and lifted on cables attached to the 12 100 tonne centrehole jacks at the top of 12 scaffold towers.

The vaults are of timber arches running diagonally, tied at 36m centres longitudinally by horizontal CHS members with operable acoustic doors suspended at these tie locations. Arches not terminating directly on ties deliver their thrusts to the ties via the triangulation inherent in the framing pattern. This means that most roof loads are concentrated at the four corner columns of each structural bay, although vertical wallposts are still needed for equilibrium local to the eaves.

The shear stiffness of the structural grid relies also on longitudinal CHS members, plus crossed tie rods inserted in the trapezium-shaped bays of the grid, to complete the triangulation. As for the dome, the purlins are attached to the timber members via stiff cleats which cantilever down and stabilise the timber sections.

Radiata pine from plantation forests in the north west part of the South Island of New Zealand was used for the vault structure, while for the dome it was mainly slash pine from Queensland, plus radiata pine form the Mt Gambier area of South Australia. End-grain embedded threaded rods connect the timber members to the steel nodes, with a coupler at the timber end face to allow bolting on of the steel shoes.

Small-scale and full-size prototype joints were tested to destruction to understand their behaviour, particularly the groups of four embedded rods. Strain gauges indicated a delivery of load into the timber close to the coupler. Pullout and failure loads indicated load factors adequate for the anchor groups in their designed condition, During erection, the steel shoes were connected at the joint centreline by end-plate bolting, with reliance on direct bearing to transfer compression.

The project has won numerous awards, including the Institution of Structural Engineers (UK) Special Award for 1999, and the ACEA Special Merit Award, 1998.

Figure 1. RAS Exhibition Halls, Homebush Bay

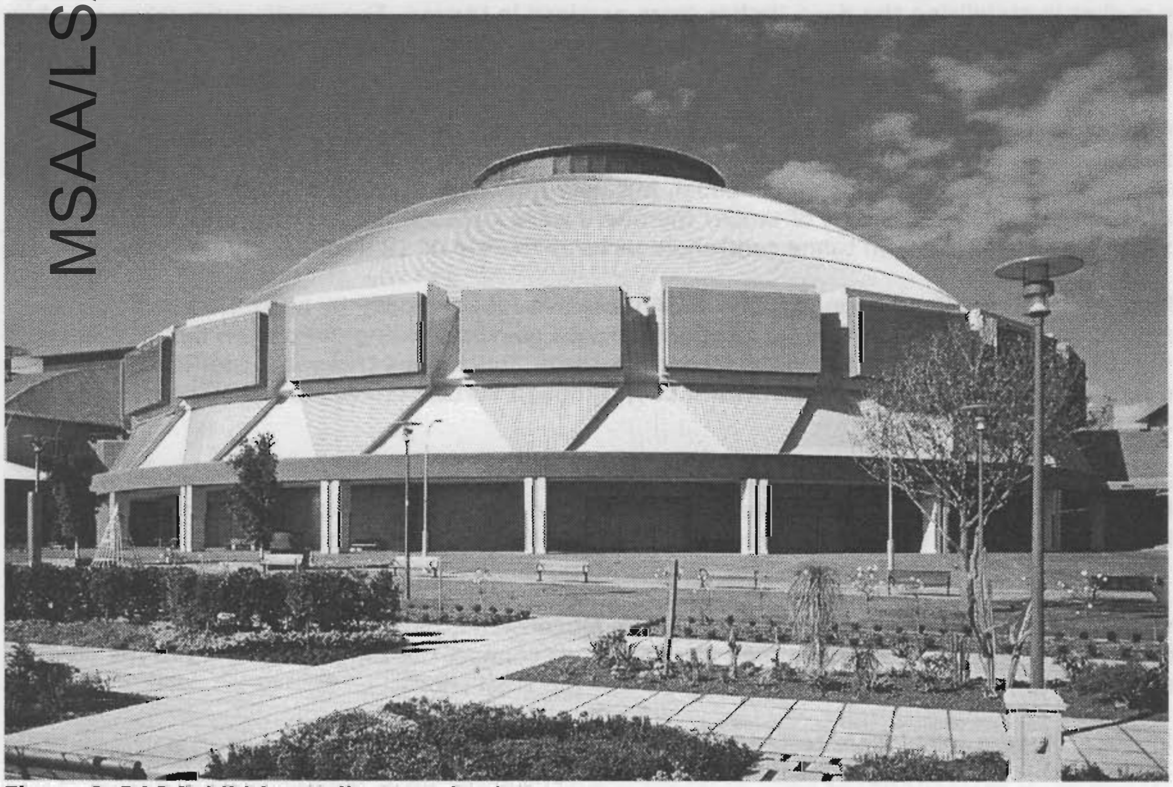

Figure 2. RAS Exhibition Halls, Homebush Bay

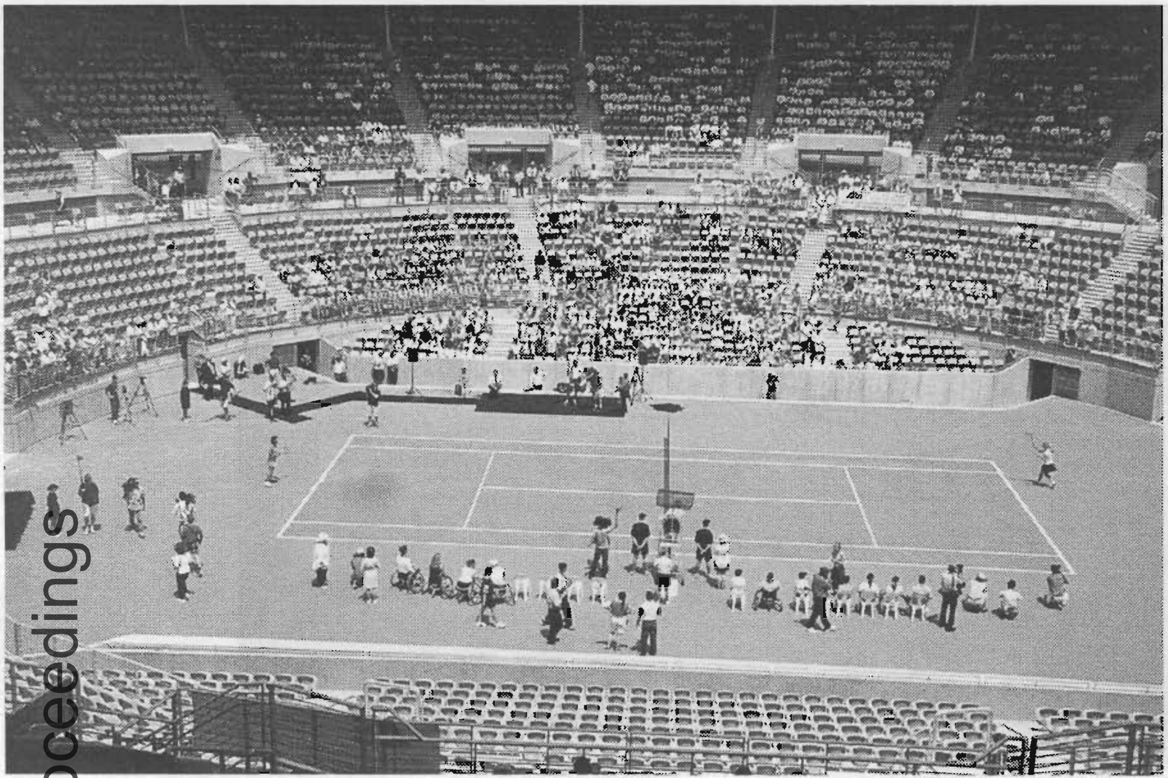

Figure 3. Sydney Olympic Tennis Centre, Homebush Bay

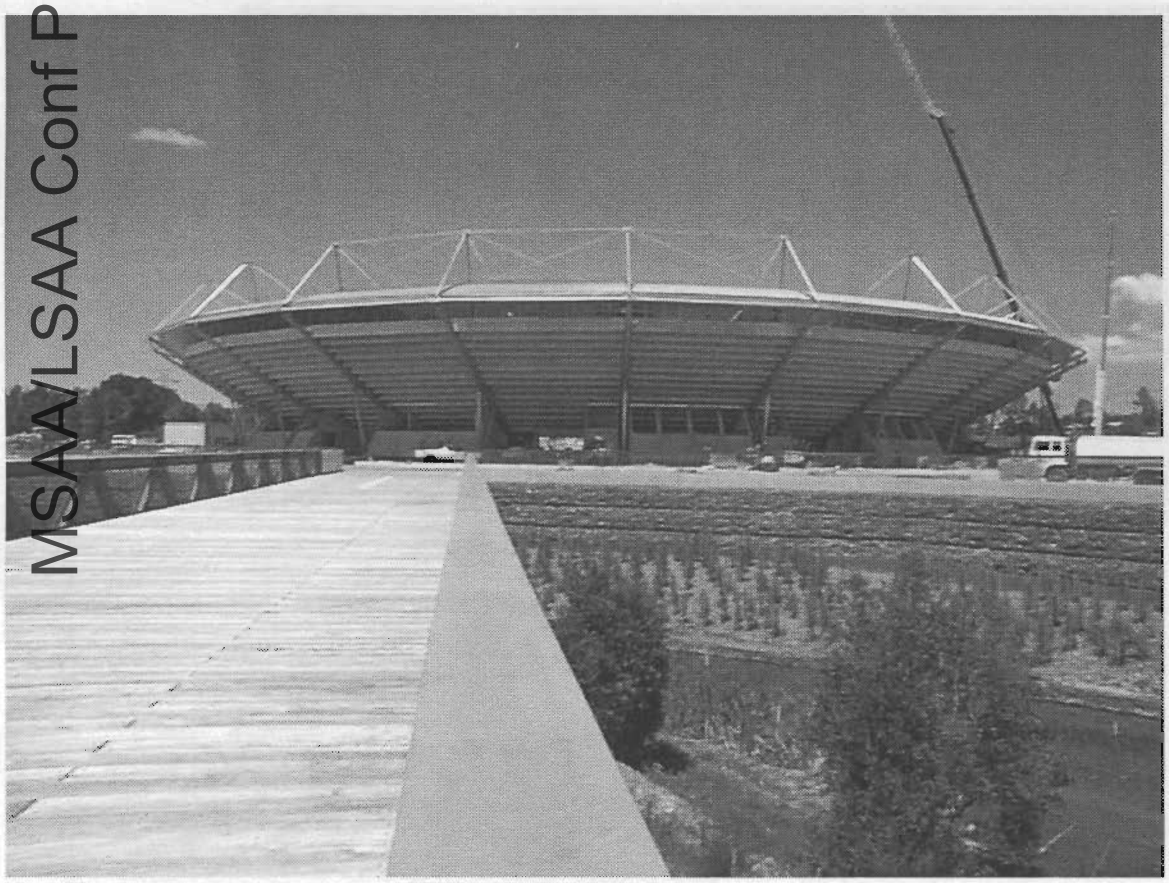

Figure 4. Sydney Olympic Tennis Centre, Homebush Bay

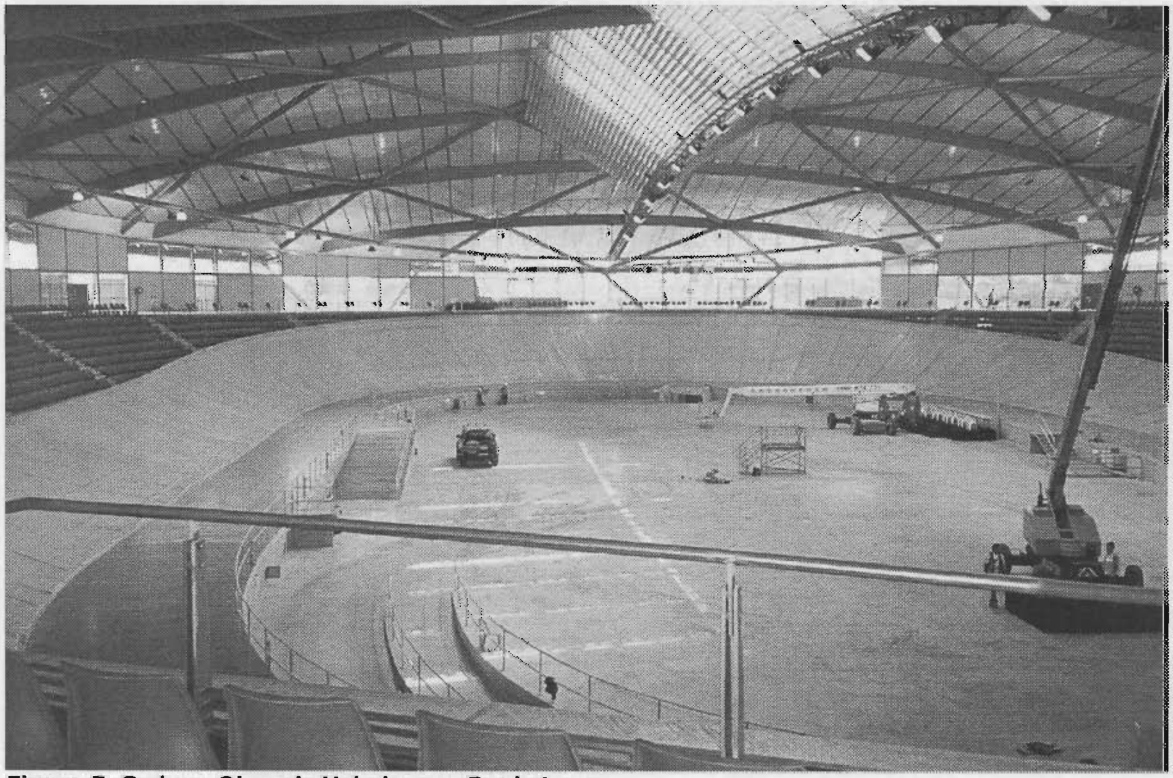

Figure 5. Sydney Olympic Velodrome, Bankstown

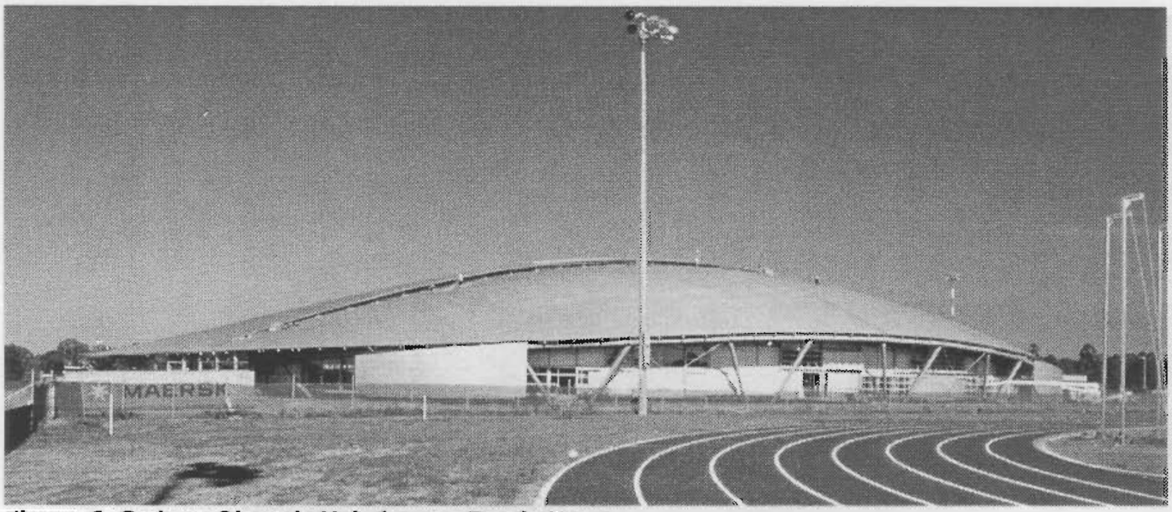

Figure 6. Sydney Olympic Velodrome, Bamkstown